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Rapid glaciation and a two-step sea-level plunge into

The Last Glacial Maximum

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22

23 **The ~10 kyr-long Last Glacial Maximum (LGM), prior to the termination of the last ice**
24 **age, was the coldest period in Earth’s recent climate history¹. Relative to the Holocene,**
25 **atmospheric CO₂ was about 100 ppm lower and tropical sea surface temperatures were**
26 **about 3-5 °C colder^{2,3}. The LGM began when global mean sea level (GMSL) abruptly**
27 **dropped by ~40 m at ~31 kyr ago⁴ and was followed by ~10 kyr of rapid deglaciation into**
28 **the Holocene¹. The masses of the melting polar ice sheets, the change in ocean volume and**
29 **hence GMSL are primary constraints for climate models constructed to describe the**
30 **LGM-Holocene transition and future changes, but important facets of the transition –**
31 **including the rates, timing, and magnitude – remain enigmatic. Here we show that sea level**
32 **at the shelf edge of the Great Barrier Reef (GBR) dropped by ~20 m from 22-21.5 ka, to**
33 **-118 m below modern. Our findings are based on recovered and radiometrically-dated**
34 **fossil corals and coralline algae assemblages, and represent relative sea level (RSL) at the**
35 **GBR, rather than GMSL. Subsequently, RSL rose at a rate of ~3.5 mm/yr for ~4 ky. The**
36 **rise is consistent with the warming previously observed at 19 kyr ago^{1,5}, but we now show it**
37 **occurring just after the 20 m RSL drop and related increase in global ice volumes. The**

38 **detailed structure of our new record is robust as the GBR is remote from former ice sheets**
39 **and tectonic activity. RSL can be influenced by the Earth's response to regional changes in**
40 **ice and water loadings and may significantly differ from GMSL. Consequently, we used**
41 **glacio-isostatic (GIA) models to derive GMSL, and find that the LGM culminated in a**
42 **GMSL low of about -125 to -130 m.**

43 The LGM to Holocene sea level rise was at times episodic and stimulated particular patterns in
44 coral reef growth and evolution. Estimates of the maximum volume of excess ice and amount of
45 water that contributed to the change in the corresponding GMSL was originally based on the
46 stratigraphy of radiocarbon and U-series dated corals from Barbados^{6,7}. Data from radiocarbon
47 dated micro and macro fossils also helped define LGM paleo-shorelines from Sunda Shelf in
48 South China Sea⁸ and Bonaparte Gulf of Northern Australia^{5,9}. However, large uncertainties
49 remain in local relative sea level data and in GIA model inputs, such as ice histories and Earth
50 rheology. These are needed in estimating the bounds of past and future global mean sea levels
51 which, for the LGM, range from 115 m to 135 m^{4,10}.

52 Precise and accurate sea level histories, often derived from dating of fossil corals and algae, are
53 important. Coastal shelf geometry and location of land-bridges and islands at the LGM have a

54 bearing on probable human migration routes and impact the ecological and species diversity, for
55 example, of endemic flowering plants on islands that had complex, dynamic histories and
56 covered a larger area during the LGM¹¹. Sea-levels vary with polar ice volumes and the extent
57 of LGM ice-sheets can affect atmospheric pressure patterns and alter the salinity of oceans
58 causing circulation changes⁴.

59 Fossil coral and coralline algae deposits of the LGM-Holocene period at the GBR are below
60 present sea level and were drilled during the Integrated Ocean Drilling Program (IODP)
61 Expedition 325 in 2010¹² (Fig.1). Corals and coralline algae were recovered from 34 holes, over
62 two transects 500 km apart, at Hydrographers Passage (HYD-01C) and Noggin Pass
63 (NOG-01B; Fig.1). Depths, up to 150 m below sea level were reached to access the full LGM
64 period¹². Selected, well characterized, samples were dated by U-series (coral) and accelerator
65 based radiocarbon (coral and algae) methods (Extended Data Table 1). Sea level depth
66 uncertainties depend on the paleo-habitat depth range of particular coral and algae species and
67 were conservatively assessed in conjunction with associated algal crust thickness, vermetid
68 gastropods and by benthic foraminiferal assemblages^{12,13} (Figs. 2, 3; Methods; Extended Data
69 Figures 1-6).

70 A brief outline of previous determinations of the timing and duration of the LGM shows it
71 extended from about 29.5 to 19 ka¹. There is an initial rapid (>40 m) fall in GMSL from 31-32
72 ka to 29-30 ka (Fig. 4a, 4b)^{1,4}. A protracted gradual GMSL drop was construed from about 29
73 ka to 21 ka⁴. However, this was largely an extrapolation between the two endpoints due to the
74 sparsity of data which also have large (~20 m) uncertainties in RSL elevations (Fig 4c, 4e)^{4,5,6,7}.
75 Onset of deglaciation is apparent from 21 ka with a gradual 10-15 m GMSL rise⁴ followed by a
76 short stable or possibly slowly falling GMSL from ~18 ka to ~16.5 ka (see Figs. 4a, 4b of Ref.
77 4). From here on, the deglaciation proceeded at a fast pace, at times, exceeding ~12 m/ky during
78 the so-called meltwater pulses^{14,15}.

79 We have converted our new GBR local sea levels to global values through GIA modelling
80 (methods) which accounts for the higher GBR coastline elevations due to increased ice volumes
81 and reduced adjacent ocean water loading. The present results significantly diverge from earlier
82 determinations and completely revise the internal structure of the LGM GMSL (Fig. 4b). A
83 large number of data points from Noggin and Hydrographers sections show a relatively constant
84 sea level from about 28 ka to 22 ka after the initial rapid fall from 31 ka⁴ as documented
85 previously from Barbados, Huon and Bonaparte Gulf (Figs. 3, 4c-4h). The GMSL remains

86 invariant from 30 ka to 21.5 ka at mean value of 113 m within a range of about ± 6 m and
87 represents the early LGM period, LGM-a (Fig. 4b; red band). This is significantly shallower
88 than former estimates⁴ (Fig. 4b). The previously identified^{16,17} ~ 19 ka, “onset-of-deglaciation”,
89 in fact, corresponds to a rapid sea level fall followed by a $\sim 4,000$ year-long ~ 3.5 m/kyr sea level
90 rise. We label this period as LGM-b, lasting from about 21 ka to 17 ka. The minimum GMSL at
91 LGM-b ranges from about 130 m to 125 m due to analytical uncertainties and uncertainties in
92 Earth model parameters and occurs after a ~ 20 m drop (Methods, Extended Data Fig. 8,9 and
93 Table 1). This point defines the start of LGM-b, after which the GMSL slowly rises to 120 m at
94 about 17 ka followed by a rapid transition towards full deglaciation. The rate of net ice mass
95 gain or sea-level fall at the inception of both the LGM-a (~ 30 ka) and LGM-b (~ 21 ka) are
96 similar and range approximately from 15 to 20 mm per year as determined from the slopes of
97 the GMSL curves. This GIA modelled, very fast, maximum glaciation rate is significantly
98 faster than the mean LGM-Holocene deglaciation rate of ~ 12 mm/year⁴. The sea-level drop at
99 LGM-b is strikingly evident in cores from both HYD and NOG sections as a major growth
100 hiatus in cores M0031-33A and M0055A 33 (Fig. 2). Deposits of fresh water calcite cement, in
101 corals below the hiatus, indicate subaerial exposure and low sea levels (Methods; Extended

102 Data Figure 5). In turn, the gap corresponding to the sea-level low is picked up at five other
103 sites, M0035, 36, 39, 53 and 54, at lower elevation, to complete the sea-level curve (Extended
104 Data Fig. 3).

105 We have established an ice model, based on the new GBR RSL data that provides a good
106 agreement with other far-field RSL records when combined with a range of Earth model
107 parameters that span the possible range of viscosities for the upper and lower mantle as well as
108 lithospheric thickness. Model predictions of RSL's, over the LGM-a and -b periods, generally
109 agree well with the trends derived from existing data (Fig. 4, Extended Data Figure7;
110 Supplementary Information). The magnitude of the sea level drop at the start of the LGM^{1,4}
111 (≈ 29 ka) is about 40 m, constrained by coral data from Huon Peninsula¹⁸ and Barbados¹⁹ and
112 with foraminifera oxygen isotope records from the Red Sea²⁰ within relatively large (ca. 10 m)
113 uncertainties. There is also close agreement between model results and data over the
114 deglaciation period from 17 ka onwards except at Barbados (Fig. 4c). Here, the systematic
115 overshoot of the data above the sea level curve is indicative of additional processes, possibly, of
116 tectonic nature¹⁵. This is consistent with independent evaluations including the study¹⁰ using the
117 rate of change of degree-two harmonics of Earth's geopotential due to GIA.

118 The very rapid build-up of global ice volume during the two periods of transition at LGM-a
119 (~29-31 ka; Ref 4, Fig. 4D) and LGM-b (~22-21 ka; Fig. 4b, present work) requires substantial
120 moisture transport and snow precipitation over existing ice sheets. To accommodate LGM-b an
121 additional equivalent ice volume corresponding up to 17 m of sea level is required. The location
122 of the extra ice cannot be determined with certainty. GIA modelling and Northern and Southern
123 Hemisphere (NH, SH) bipolar climate paced by complementary high latitude insolation highs
124 ^{1,21,22} at these times shows increased ice volume over the North American Ice Sheet (NAIS) at
125 LGM whereas the Eurasian ice sheet appears to have grown at a slower pace and commenced
126 melting after ≈ 22 ka (Extended Data Fig. 8). Colder Antarctic climate during the LGM^{3,16} is
127 likely to have hindered ice calving and lessened basal melting of ice shelves resulting in
128 increased ice volume. The sustained growth of the AIS during the LGM-b period and beyond,
129 including continuing ice accumulation up to around 14 ka, agrees with observations of the late
130 retreat of West Antarctic Ice Sheet at this time ^{1,23,24}. However, the major increase in ice
131 volume, precipitating the onset of LGM-b, appears to have been during a short period (20 ka to
132 21 ka) over the NAIS after which the NAIS retreated from ≈ 20 ka onwards²⁵ (Extended Data
133 Fig. 8).

134 The enlarged global ice volume at ~30 ka^{1,4,18,26}, equivalent to ~40 m of sea-level drop, persisted
135 for over ~8 thousand years. Similarly, the low NH insolation and somewhat reduced
136 atmospheric CO₂ levels around ~21 ka to ~22 ka led to a period of cold climate, very low
137 tropical Atlantic SST's and ultimately the transition to LGM-b. At this time, increased SH
138 insolation is likely to have facilitated moisture transport to the South, increasing the AIS
139 volume^{1,18,27}. Heinrich event 1 at ~17 ka marks the end of LGM-b when full deglaciation
140 kicked-in as the pace of NH insolation and atmospheric CO₂ levels increased rapidly (Fig. 4).

141 The two sharp transitions preceding LGM-a and LGM-b periods, associated with rapid
142 accumulation of ice and lower sea levels, at the end of the last ice age, do not appear to be
143 explicable in terms of processes attributable to any specific climate-change dynamic. During
144 this time (~29-19 ka), oxygen isotope records in ice cores do not show a clear, distinct signal;
145 the CO₂ levels were stable, insolation at the time was not so different to present and tropical
146 SST did not change significantly^{1,28}. A systematic behaviour in sea level and climate has
147 previously been noted²⁹ whereby transitions between two states, cold to warm or warm to cold,
148 took place through a third more extreme state as in MIS3-LGM-Holocene or during the Last
149 Interglacial (LIG), LIG-(LIG high-stand at the end of LIG)-(MIS 5d). A similar behaviour in

150 climate was previously noted where the appearance of an intermediate, extreme third state, may
151 have resulted in a shift from “41-ky” cycles to “100-ky” cycles 800 ka to 1 Ma ago³⁰. These
152 bifurcations can be thought of as states in three climate potentials with “stochastic climate
153 noise” causing transitions between them³⁰. Here, it appears that the same behaviour may occur
154 over short timescales, not only over 100 ka cycles. The transitions are not only manifest in
155 climate but are also associated with sea-level change.

156

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252 J.M.W., A.L.T., J.C.B, M.H., and the paper was refined by contributions from the rest of the
253 co-authors.

254 **Competing interest** The authors declare no competing interests.

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257 **Figure Legends**

258 **Figure 1**

259 **Location of GBR Expedition 325 study site.** The Northern and Southern sites are at Cairns

260 (Noggin Pass – NOG01B) and at Mackay (Hydrographer’s Passage – HYD-01C).

261 High-resolution 3D multibeam image showing the surface geomorphic context¹², drill transects

262 and specific locations of the drill holes.

263 **Figure 2**

264 **Last Glacial Maximum sea level drop at LGM-b.** Here, captured clearly as a distinct age

265 discontinuity observed in cores M0055A and M0031-33A from NOG and HYD transects

266 respectively, separated by more than 500 km in the GBR. Cores obtained from different fossil

267 GBR terraces and reefs reveal the trajectory of past sea level changes. Five reef sequences are

268 distinguished based on the IODP Exp. 325 record: Reef 1 (≥ 30 ka), Reef 2 (27-22 ka), Reef 3

269 (3a, 21-17 ka; 3b, 17-13 ka), Reef 4 (13-10 ka), and Reef 5 (modern GBR). The major growth

270 hiatus evident from both HYD and NOG sections marks the death of Reef 2 (22.1 ka to 21.9 ka)

271 following the sea level fall leading to LGM-b and reestablishment of reef (Reef 3a) further

272 seaward at 20.7-20.5 ka (Extended Data Figs. 3, 4, 5). The age versus depth relationships, and
273 the presence of fresh water low magnesium calcite cement, in Reef 2, confirms subaerial
274 exposure during the LGM-b period. In contrast, their absence below Reef 3a deposits places a
275 maximum limit on the sea level fall (Methods). At the end of LGM, after 17 ka, sea level rose
276 rapidly flooding the outer shelf causing the re-establishment of the reef over its former position
277 (Reef 3b), marking the end of hiatus at the top of Reef 2 at ~17 ka. The details of the transition
278 to LGM-b and the critical samples defining the fall in sea-level are shown in Extended Data Fig.
279 6.

280 **Figure 3**

281 **Age versus depth plots showing the RSL envelopes derived from samples recovered by**
282 **IODP Expedition 325.** Both HYD (panel a, blue) and NOG (panel b, red) transect cores were
283 examined for coral, coralgall algae and benthic foraminiferal assemblages (Extended Data Figs.
284 1, 2) with help of X-ray CT scan and X-ray diffraction (Supplementary Information) that
285 revealed detailed features of relative sea level histories during the past 35,000 years. The >500
286 dates, selected through detailed sedimentologic and biologic analyses (Methods), provided a
287 robust chronostratigraphic framework that defined five distinct reef sequences (Reefs 2 to 4 are

288 labeled on Fig. 2) which grew episodically over the past 30 ka. The RSL's constructed here
289 depend on the age (horizontal grey line) and sea level depth uncertainties (upward and
290 downward grey lines) related to paleo-habitat depth range (upward line) of each dated coral or
291 algal sample and the maximum coring depth uncertainty (downward line). The paleowater depth
292 ranges for shallow water species (blue and red envelopes) were conservatively estimated using a
293 multiproxy approach combining coral, coralline algae and other key indicators such as algal
294 crust thickness, and the presence of vermetid gastropods (Methods, Extended Data Table 1).
295 Note the disconnected paleowater depth lines on some samples are indicative of deeper habitat
296 ranges likely > 20 m water depth. The distribution of marine and fresh water cements in the
297 cores were used to support the new estimates of the timing and magnitude of the LGM-b sea
298 levels (Extended Data Figs. 3-5), including hiatuses and regressions.

299 **Figure 4**

300 **Global mean sea levels (GMSL) and GIA model derived far-field RSL with observational**
301 **data.** Previously constructed global mean sea level curve over the past 140 ka⁴, blue line in panels
302 a, b, is shown together with GIA model predictions, in panels c-h, for selected far-field data
303 represented by red circles with depth and age error bars. High latitude (65 °) summer insolation

304 curves for Northern and Southern Hemispheres in panel (b) are shown as dashed orange and
305 blue lines respectively. Long term sea level variation is in step with Northern Hemisphere
306 summer insolation whereas LGM-b occurs at the peak of Southern Hemisphere insolation.
307 Orange circles in each panel (c-h) indicate previously reported RSL with depth and age
308 uncertainties (horizontal and vertical black lines). Results of 62 GIA model runs (Methods),
309 over a range of potential earth model parameters, such as lithospheric thickness and viscosities
310 of both upper and lower mantle, are within the orange (a-b) and gray bands in (c-h). The red and
311 blue curves in grey shaded bands (c-h) show the results for lower mantle viscosities of 10^{22} and
312 10^{23} Pa s respectively with 70 km lithospheric thickness and upper mantle viscosity of 10^{20} Pa s.
313 Of note is the foraminiferal oxygen isotope based Red Sea data²⁰ (h) which supports the new
314 GMSL calculations from the present study within uncertainties (ca. 10 m). The orange band in
315 (h) is confidence intervals of 95% for the RSL data (light orange) and probability maximum
316 (dark orange) reported in ref. 20.

317

318 **Methods**

319 **IODP Expedition 325: The Great Barrier Reef environmental changes.**

320 The Integrated Ocean Drilling Program (IODP) Expedition 325 was designed to complement
321 the previous IODP “Tahiti Sea Level” Expedition 310 to Tahiti³¹. In preparation for Expedition
322 325, potential drill sites were surveyed with the CSIRO ship *RV Southern Surveyor* using
323 multibeam sonar, seismics, an AUV and rock dredging^{12,32}. At most of the Great Barrier Reef
324 (GBR) locations, the shelf breaks at approximately 120 m and is populated with prominent
325 terrace-like structures and other relict reefs appear successively at 100-90 m, 60-50 m and 35-40
326 m depths³³⁻³⁵.

327 The mission specific platform chosen for Expedition 325 was the *Greatship Maya*, an IMO
328 class II vessel capable of being positioned dynamically for *geotechnical* coring^{32,35}. The
329 expedition took place between 12 February and 6 April 2010. A total of 34 holes across 17 sites
330 were sampled ranging in depth from 46.4 m to 170.3 m such that the recovered corallgal deposits
331 span several crucial but poorly defined periods during the LGM and last deglaciation. Sampling
332 occurred at three locations along the North Eastern coast of Australia but this study focuses on
333 one transect at 19.7° latitude offshore from Cairns at Noggin Pass (NOG-01B), and another at
334 17.1° latitude, offshore Mackay at Hydrographer’s Passage (Fig. 1, HYD-01C). Photographs of
335 half-sectioned reef cores, relevant to the present study, are shown in (Extended Data, Figs. 1, 2)

336 together with the depths and genera of the dated corals and coralline algae. Classification of
337 coral genera and species in terms of their habitat preferences according to depth and turbulence
338 levels is also supported by considering the habitats of associated coralline algae taxa and crust
339 thickness and vermetid gastropods. For example, individual coralline algae can have limited
340 range of habitats bounded by sensitivity to light levels, wave energy and other factors and can
341 be used to more accurately constrain the paleo-depth ranges. Based on this careful and detailed
342 multi-proxy approach each dated coral and coralline algae sample was placed within an
343 internally consistent coralgal assemblage and paleobathymetric scheme^{36,37} enabling the
344 construction of an independent RSL envelope at each site (Extended Data Figs. 1, 2, 3, Table 1
345 and Supplementary Information).

346

347 **Main lithologic facies observed in the Expedition 325 cores.**

348 The main lithologies are divided into coral reef framework and detrital sedimentary facies. The
349 three boundstone facies are defined by their varying proportions of corals, coralline algae and
350 microbial deposits forming coralgal, coralgal-microbialite and microbialite-dominated
351 boundstones. The detrital facies can occur locally as internal sediments within the boundstones,

352 or as metre scale intervals of packstones to rudstones and unconsolidated sediments. Details of
353 facies and depth estimate using facies as well as coral and coralline algae assembly can be
354 found in Extended Data Figures 1 and 2 and Table 1, and are derived from Webster et al.¹².

355

356 **Reef 2 hiatus and GMSL drop to LGM-b**

357 A major growth hiatus is observed in the inner shelf terrace at 104-106 mbsl, at both HYD-01C
358 M0031-33A) and NOG-01B (Hole M0055A) (Extended Data Figs. 3 and 4)¹². This represents
359 the turn-off of Reef 2 at ~ 21 ka and is interpreted to be caused by the drop in sea-level to the
360 LGM-b. The corallgal assemblages show that paleowater depths were shallow (<10 m) just prior
361 to Reef 2 death, and lithologic, and seismic evidence indicates this was a major subaerial
362 exposure surface¹². Furthermore, detailed scanning electron microscopic (SEM),
363 energy-dispersive X-ray spectrum (SEM-EDS), X-ray diffraction (XRD) analyses and
364 thin-section observations of Reef 2 deposits confirm that they were exposed to freshwater or
365 subaerial environments (e.g. low magnesium calcite cements in Hole 55A Core 4R1) during the
366 sea level lowstand at LGM-b (Extended Data Fig 5). At this time shallow reef development
367 migrated ~1 to 0.25 km seaward (ie. Reef 3a) in <2 kyr, as the RSL sea level fell to 118 m

368 below present by ~20.5 ka. The Reef 3a deposits and the older > MIS3 deposits are
369 characterized by wholly marine diagenetic features consistent with the interpretation that the
370 LGM-b sea level did not fall below this level (Extended Data Fig 6). Sea level rose during the
371 deglacial causing major Reef 3a aggradation¹² before re-flooding the inner shelf terraces at ~
372 16.5 ka and causing the re-establishment of the reef (Reef 3b) over its former position, marking
373 the end of the hiatus at the top of Reef 2.

374

375 **Determining the ages of sea level indicators**

376 Representative, more than 165, coral skeletons and their aragonite content were analyzed by
377 powder X-ray diffraction, X-radiography, SEM and petrologic investigations, all of which
378 confirmed to the pristine nature of the dated samples². In a few cases, X-ray diffraction picked
379 up minor signatures of Hi-Mg calcite, likely due to trace amounts of coralline algae and
380 microbialite sediment. Yet no significant calcite peaks were observed in most of the cases.
381 Physical cleaning of branched corals for U-Th dating and severe acid dissolution of samples,
382 namely more than 50% of the weight, for radiocarbon dating was used to remove potential
383 secondary precipitated materials. For massive *Porites* corals, physical cleaning is difficult

384 requiring further geochemical tests including ICP-MS. Skeletal Mg/Ca ratios confirmed the
385 absence of significant amounts of high-Mg calcite and secondary aragonite cements. Even the
386 case when the secondary aragonite was found, the ages are not affected significantly since the
387 form of the cements are indicative of early phase of post mortem of corals. Further evaluations
388 included limits on total uranium, ^{232}Th content and initial $^{234}\text{U}/^{238}\text{U}$ ratio. We applied different
389 initial $^{234}\text{U}/^{238}\text{U}$ criteria: for samples of the deglacial period between 17 ka and 0 ka, the
390 acceptable range was 1.1452 ± 0.0140 , whereas for the samples from 30 ka to 17 ka 1.1402
391 ± 0.0140 was used. All of data used to reconstruct the relative sea level envelopes for each
392 transect are shown in Supplementary Information (see Methods Section *Relative Sea level (RSL)*
393 *reconstruction* for more details) and the primary samples used to determine the specific RSL
394 inflection points are indicated as “HY-1, 2..” and “NO-1, 2..” for HYD-01C and NOG-01B
395 respectively in the Supplementary Information and highlighted in bold. U-series and
396 radiocarbon ages from the same coral samples also showed remarkable consistency, along with
397 radiocarbon ages on directly adjacent coralline algae. Taken together, and combined with the
398 consistent reproducibility of the relative sea level envelopes between two transects, more than
399 500 km apart, confirms the veracity of the data.

400

401 **Radiocarbon dating**

402 More than 500 radiocarbon dates were obtained using corals and coralline algae samples which
403 were all processed at the Atmosphere and Ocean Research Institute (AORI), the University of
404 Tokyo (UTokyo) to convert them into graphite³⁸. Typically 1mg or more of graphite was
405 measured using a Single Stage Accelerator Mass Spectrometry at AORI³⁹ and at the Australian
406 National University (ANU; ⁴⁰). The results were then converted to calendar ages with local
407 reservoir ages (12 ± 10 years) from⁴¹, which we obtained by averaging between Heron Island
408 (8 ± 6 years) and Abraham Reef values (15 ± 6 years). The calibration was then performed using
409 international calibration datasets (IntCal 13 and Marine 13;⁴²)

410

411 **Analytical procedures, Mass spectrometry and U-Th dating.**

412 The analytical data are listed in Supplementary Information. Consistency between labs for
413 replicate measurements of a single specimen is within 100 years, which is similar to the intra
414 coral variability observed in some specimens measured using the high precision (WHOI)

method. Uranium series dating were conducted at three different labs: the Australian National University (ANU), the University of Oxford (OX) and the Woods Hole Oceanographic Institute (WHOI). A 61-cm mass spectrometer is used at ANU, which can operate in charge-mode⁴³. The ²²⁹⁻²³⁰⁻²³²Th isotopes were measured simultaneously in charge-mode in Faraday cups using 20pF feed-back capacitors as active electrometer elements. Uranium isotopes, ²³³⁻²³⁴⁻²³⁵U were also measured in charge-mode, whereas ²³⁸U was simultaneously measured using a 10¹⁰ Ohm feed-back resistor. The magnitude of the ²³⁸U low-mass tail was monitored continuously at mass ²³⁷U in charge mode. This was used to subtract the ²³⁸U tail from under the ²³³⁻²³⁴⁻²³⁵U isotopes. Extensive measurements with an un-spiked U-standard HU-1 showed that the shape of the ²³⁸U tail remained invariant under a wide range of conditions, in particular, at the expected locations of the ²³³⁻²³⁶U peaks. Sample loads, on single rhenium filaments, ranged from 0.5 to 0.8 µg and the ²³⁸U beam intensity was kept between 8x10¹¹ to 10x10¹¹ Ampere for several hours. At these intensities, 10¹⁰ Ohm feedback resistor was used to avoid response-time problems encountered with the considerably slower 10¹¹ Ohm resistors. The instrument was calibrated with reference to a secular-equilibrium standard HU-1. Comparisons with Western Australian last interglacial samples⁴⁴ and with Hulu-Cave speleothem data⁴⁵ showed precise agreement with previous

431 measurements. Sample processing followed previously established procedures⁴⁶. U and Th were
432 separated from the coral carbonate using U-Teva resin in a single pass.

433

434 Uranium thorium dating at OX and WHOI were measured by multi-collectors ICP-MS. At OX,
435 U and Th isotopes were measured with ion counter collectors for the minor isotope beams.
436 Approximately 0.3g of coral sample was dissolved and spiked with a mixed ²³⁶U:²²⁹Th tracer. U
437 and Th were purified and measured separately: U isotopes, statically; and Th by peak hopping
438 the 229 and 230 beams into an ion counter while normalizing beam intensity between the steps
439 with either ²³²Th or ²³⁵U measured in Faraday collectors. Instrumental biases and relative
440 collector efficiencies are accounted for using standard sample bracketing using U and Th
441 isotope standards⁴⁷.

442

443 At WHOI U and Th isotopes were measured by MC-ICP-MS in static mode with all isotopes in
444 Faraday collectors⁴⁸. Large ~5g subsamples of coral were dissolved and spiked with a mixed
445 ²³³U:²³⁶U:²²⁹Th tracer, optimised for the last glacial maximum to deglacial age samples, and

446 co-precipitated with Fe. To determine the $^{230}\text{Th}/^{238}\text{U}$, purified U and Th fractions are
447 recombined such that U and Th are measured together at isotope ratios that can be closely
448 matched to bracketing standards. The $^{234}\text{U}/^{238}\text{U}$ is similarly determined statistically in Faraday
449 collectors but on an unspiked aliquot.

450

451 All activity ratios and ages are calculated using the half-lives reported in⁴⁵. Ages are presented
452 in Extended Data Table 1 as ‘raw’, assuming all ^{230}Th is accumulated in the coral since growth,
453 and an age corrected for detrital ^{230}Th . The detrital correction makes use of the measured
454 $^{232}\text{Th}/^{238}\text{U}$ as a proxy for the amount of detrital contamination, an assumed detrital composition
455 of crustal origin⁴⁹, and an allowance for non-secular equilibrium of the contaminant.

456

457 **Relative sea level (RSL) reconstruction**

458 The sample context was assessed using established criteria^{12,32} including: (1) core quality, (2)
459 orientation of well-preserved corallites; (3) thick coralline algal crusts capping upper coral
460 surfaces; (4) evidence of substrate attachment; and (5) the presence/absence and orientation of

461 geopetals in lithified facies . Based on these criteria all the samples were classified into the
462 following four context categories: (1) IS = in situ (convincing supporting evidence), (2) IS? =
463 likely insitu (inclusive supporting evidence), (3) ISX = not in situ (convincing nonsupporting
464 evidence, and (4) ISN = status not known (inadequate evidence either way). Samples from
465 highly drill-disturbed or poor recovery intervals were excluded. A total of 540 samples
466 satisfying these criteria were used to construct a RSL envelope (upper and lower bounds) at
467 both sites. Despite known temporal differences in ocean reservoir age, the coral U/Th and
468 coral/coralline ^{14}C AMS ages are remarkably consistent. However, wherever possible we used
469 the more precise U/Th coral ages to constrain the upper and lower bounds of the envelopes. This
470 was achieved by visually fitting a line through the dates that were >1 m apart and outside their
471 analytical age errors, while also taking into account the upper bound of the paleowater depth
472 estimate of each sample and any core recovery uncertainties (Supplementary Information).
473 Where multiple coral dates overlapped (in time) we used the mid-point between samples. If
474 replicate age determinations were available for the same sample (ie. same coral colony or
475 coralline algal crust) (Supplementary Information) an average age was calculated and plotted on
476 Fig. 3. The upper bound or minimum position of the sea level envelope was further constrained

477 by considering the overlapping paleowater depth ranges of both the shallow water sea level
478 indicators and their coeval, deeper forereef slope equivalents. Finally, the major inflection
479 points marking clear changes in the direction, amplitude and rate of RSL change were also
480 identified each envelope (Fig. 3). Thus the lower bound (i.e. maximum sea level position) of
481 RSL curves and the specific samples defining them are indicated in bold in Supplementary
482 Information (ie. HY-1, 2., NO-1, 2..) and a close up of the key samples constraining LGM-b is
483 also shown in Extended Data Figure 6.

484

485

486 **GIA model predictions**

487 The GIA model calculations included an earth model describing the viscoelastic properties of
488 the solid earth, as well as an ice component documenting the ice melting history, reconstructed
489 mainly from far-field sea-level observations^{4,50}. The Earth model is based on seismologically
490 derived “Preliminary Reference Earth Model” (PREM)⁵¹ and consisted of an elastic lithosphere
491 with an upper and lower mantle divide at 670 km depth. The lithosphere thickness was 70km

492 and upper and lower mantle viscosities ranged from $(1-10) \times 10^{20}$ Pas and $(1-100) \times 10^{22}$ Pas
493 respectively. This model provides an accurate treatment of time-dependent continental
494 shorelines⁵² and the Earth rotation feedback on sea level⁵³.

495 The ice model described above was adjusted to match the newly obtained (RSL) records from
496 the Great Barrier Reef. The analytical uncertainties in RSL were taken into account and the
497 shallow and deep extremes of the RSL envelope were tested. We first employed the ice history
498 model developed by ANU group⁴ and ran the GIA model to obtain relative sea level histories
499 for the GBR. The ANU ice model with the same relative ice volumes was then scaled to fit the
500 NOG and HYD RSL. The scaling was done manually within a reasonable range of various
501 parameters and by keeping the relative ice volume of various ice sheets the same as in the
502 original ANU model though keeping the Eurasian ice model almost the same as the ANU model
503 since the history of this ice sheet is reasonably well constrained from both observations and
504 models⁵⁴⁻⁵⁶ compared to other ice sheets. The chosen Earth parameters (Lithospheric thickness =
505 70km, Upper mantle viscosity = 2×10^{20} Pa s, and Lower mantle viscosity = 10^{22} Pa s)^{57,58} fit
506 the GBR region Holocene sea levels well. The analytical uncertainties in RSL and the range in
507 Earth Model parameters (approximately ± 2.5 m contribution to GMSL) were used in calculating

the MAX and MIN extremes (Extended Data Figs. 8, 9 and Table 4). Supplementary Information shows Global Mean sea level contributions individually for each major ice sheet and for the ANU and highest SL and lowest SL GMSL scenarios (in eustatic terms). The two GMSL curves were then used to construct RSLs in far-field sites with previously published RSL data for comparison (Fig. 4 and Extended Data Fig. 7). Potential Earth model uncertainties were also considered with variable lithosphere thickness and a range of viscosities, of the lower as well as the upper mantle, resulting in more than 60 GIA model experiments. Shaded areas of curves represent possible ranges in RSL for individual sites (Fig. 4 and Extended Data Fig. 7). Visual inspection of the results indicate that the MAX model fits the data remarkably well for almost all the far-field locations tested. In turn, this indicates that the shallow coral habitat depth estimates appear to be sufficiently robust without necessitating extended, deeper water limits. During the last glacial maximum (30-19 ka; Fig. 3), water depth uncertainties for most samples from the HYD and NOG transects are <5m. Figure 2 shows RSL curves derived from MAX and MIN models. Various Earth rheology parameters were also tested using both MAX and MIN ice models where the shaded region around GMSLs in Extended Data Figure 9 represents the corresponding range in RSLs. During the LGM, the maximum magnitude of RSL difference

524 between the two transects is less than 10 m⁵⁹ and hence RSL variations arising from
525 hydro-isostasy are small. The models were run over the maximum possible ranges of the
526 rheological parameters so that the range of RSLs depicted as the shaded zone in Extended Data
527 Fig. 9 cover the full range of possibilities. Traditionally, lower mantle viscosity has been
528 estimated as ca. 10^{22} Pa s using far-field RSL observations^{57,58}, whereas recent studies have
529 reported much higher values of $\sim 7 \times 10^{22}$ Pa s⁴. Thus, assuming a typical lithospheric thickness
530 and upper mantle viscosity respectively of 70km and 2×10^{20} Pa s, the maximum RSL
531 differences associated with the above range of lower mantle viscosities is ca. 5m (Extended
532 Data Figure 9). This number is smaller than the typical uncertainties inherent in RSL
533 observations at the GBR and, therefore, is well suited for reconstructions of GMSLs during
534 LGM-a and LGM-b. In summary, we concluded that the MAX model provides the best estimate
535 of GMSLs as well as indicating that these tighter depth uncertainties for GBR corals¹² do
536 provide consistent results. Therefore, the extended MIN to MAX range, employed here, well
537 covers the likely range of GMSL constructions with confidence as can be ascertained by visual
538 inspection (Extended Data Figure 9).

539 Glaciological evidence, including from ice cores cannot easily accommodate the required
540 increase in ice volume. However, the total increase is shared among the large ice sheets
541 (Extended Data Fig. 8). Ice cores retrieved from Antarctica and Greenland are not able to
542 resolve the required magnitude of elevation changes in continental interiors. It is also likely that
543 current ice free regions may have been the places to retain the extra ice at these times. For
544 example, recent evidence suggests that an extensive Ice sheet was grounded on the Ross Sea for
545 at least 3,700 years⁶⁰. New bathymetric data as well as glacial models support these
546 conclusion⁶¹. However, there is still scope to improve the glaciological models and hence, we
547 hope that our data will contribute to this effort.

548 Discrepant GMSLs during the LGM at either -120 m or -140 m has been reported respectively
549 for Barbados⁷ and the Bonaparte Gulf in North Australia⁵. This has now been reconciled using
550 the recently reported Earth rheology model with J2 observations¹⁰ as well as considering
551 subducting material in Barbados⁶². The model included 65-100km of lithospheric thickness and
552 upper and lower mantle viscosities of $(1-3) \times 10^{20}$ Pa s and 10^{23} Pa s. The global relative sea
553 level observations could reasonably be explained if GMSL during the LGM was ca. -130m.
554 This finding is consistent with the model derived from more than 1,000 far-field RSL

555 observations⁴. The results from the present study, for both the MAX and the MIN options, are
556 respectively -125m and -130m and thus consistent with the independent estimates described
557 above.

558 **Data availability.** All the data used in this manuscript is available from Supplementary
559 information of online version of this paper. Modified ANU ice model is available upon
560 reasonable request.

561 **Code availability.** Model that we employed in this paper is available from J.O and Y.Y.
562 (yokoyama@aori.u-tokyo.ac.jp) upon reasonable request.

563

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666

667 **Extended Data Legends**

668 **Extended Data Figure 1 | Simplified classification of the main corallgal assemblages**

669 **observed in the Expedition 325 cores.** Shallow reef habitats are represented by coral
 670 assemblages, cA (massive/robust branching *Isopora* (1) and corymbose *Acropora* gr. *humilis*
 671 (2)), cB (branching *Seriatopora* (3), *Acropora* sp. (4)), cC massive/encrusting meruliniids (5),
 672 and cD (encrusting to massive *Porites* (6) and encrusting *Montipora*), when associated with
 673 thick crusts of aA1 coralline algae (*Porolithon onkodes*) (7, 8) and vermetid gastropods (8).
 674 Deep, fore-reef slope settings are defined by coral assemblages cD (encrusting to massive
 675 *Porites* (6) and encrusting *Montipora*, when associated with thin crusts of aA3 (*Mesophyllum*

676 and *Lithothamnion*) (10) and in the absence of aA1 & aA2 (thin *P. onkodes*, *Porolithon*

677 *gardineri*, *Harveyolithon* gr. *munitum*) (9).

678

679 **Extended Data Figure 2|**

680 **Representative facies observed in the Expedition 325 cores.** The main lithologies are divided

681 into coral reef framework (1-3) and detrital sedimentary facies (4-8).

682 **Extended Data Figure 3 |**

683 **Stratigraphic synthesis of inner terrace cores at Mackay.** The vertical patterns in coral

684 recovery, lithologies, coralgall assemblages, and vermetid gastropods are summarized here.

685 These data define a major hiatus (red line) in reef development as the top of Reef 2 was exposed

686 following the sea level fall to the LGM-b low-stand (see main text for details). Following

687 deglacial sea level rise, reef growth was re-established as Reef 3b turned on as the shelf is

688 reflooded before this reef drowned after ~14 ka

689 **Extended Data Figure 4 |**

690 **Close-up core images showing the boundary between Reef 2 and Reef 3a.** Cores
691 M00033A-10R and 11R (HYD-01C) and M00055A-4R (NOG-1B) clearly define the nature of
692 the Reef 2/Reef 3b boundary that represents a major hiatus in reef growth (see Extended Data
693 Figure 3). This boundary is characterized by major changes in lithologies, corallgal assemblages,
694 and diagenetic features, including fresh water, meteoric cements (blue star) indicating the top of
695 Reef 2 has been subaerially exposed.

696 **Extended Data Figure 5 |**

697 **Evidence of subaerial exposure.** The blocky low magnesium calcite meteoric cement that is
698 related to subaerial exposure is initially precipitated in the intergranular voids of grainstone in
699 55A 5R1. Then peloids (p) of high magnesium calcite formed under marine condition to fill
700 remaining voids due to submergence following re-flooding. Scale bar in the picture is 100
701 micrometer.

702 **Extended Data Figure 6 |**

703 **Timing and extent of the sea-level drop at LGM-b.** Age vs. depth plot showing the key in situ
704 RSL data points from Hydrographer's Passage (HYD-01C) (in blue) and Noggin Pass

705 (NOG-01B) (in red). AMS-¹⁴C-ages derived from corals are indicated by open circles and those
706 derived from coralline algae are indicated by circles with a cross inside. U/Th coral ages are
707 indicated by filled circles. Inflection points defining the maximum position of the RSL at
708 HYD-01C and NOG-01B are also displayed on the figure (see labels NO-5, 8, 9, and HY-3, 5, 6
709 in Supplementary Information, corresponding respectively to data points 11, 8, 1 and 9, 7, 5 on
710 this figure – see also Fig. 3 in the main text). The combined RSL envelope represented by the
711 black lines (maximum and minimum position) takes into account the uncertainties in the age
712 (2σ), paleowater depth and position in the core of each data point which is illustrated by a
713 colored rectangle (blue for Hydrographer's Passage and red for Noggins Pass) (see Methods for
714 more details). If we were to omit the ¹⁴C data due to possible unaccounted variability in local
715 reservoir ages⁶³, the LGM-b sea level drop defined by coral U/Th ages would be 1.5 ky earlier
716 at 23.5 ka, corresponding to an extended sea level drop over ≈ 3000 years at ≈ 7 m/ky. Key RSL
717 index points are: 1. 325-M0053A-13R-1W 21-25 (20.51 ka, 117.93 m; NO-9), 2.
718 325-M0054B-06R-1W 64-67 (20.50 ka, 124.39 m), 3. 325-M0054B-07R-1W 5-9 (20.47 ka,
719 125.3 m), 4. 325-M0035A-18R-1W 10-15 (20.43 ka, 127.11 m), 5. 325-M0036A-18R-2W 8-10
720 (20.70 ka, 128.75 m; HY-6), 6. 325-M0054B-08R-2W 73-75 (22.13 ka, 128.54 m), 7.

721 325-M0033A-11R-CCW 5-11 (22.11 ka, 106.83 m; HY-5), 8. 325-M0055A-04R-1W 35-40b
722 (21.87 ka, 103.13 m; NO-8), 9. 325-M0032A-10R-1W 18-20 (23.49 ka, 107.95 m, HY-3), 10.
723 325-M0033A-13R-CCW 1-3 (23.62 ka, 109.46 m), 11. 325-M0055A-04R-2W 99-105 (23.97
724 ka, 104.84 m; NO-5).

725 **Extended Data Figure 7 |**

726 **GIA results for selected sites.** Calculations, for selected far-field sites (a-f), using the ice model
727 based on the lower-bound of RSL from GBR. GIA calculations implemented using parameters of
728 upper mantle viscosity and lithospheric thickness 10^{20} Pa s and 70 km and lower mantle viscosity
729 of 10^{22} Pa s. However, the differences between data and calculations for far-field sites of
730 Tahiti (b), Bonaparte (c) and Sunda(d) indicate a better match with GIA when the higher RSL
731 obtained from this study is used (Fig 4) in calculating the global deglacial sea levels. The grey
732 band represents the range of RSL predictions using GIA modelling with various earth parameters
733 (Lithospheric thickness $H = 70\text{km}$, Upper mantle viscosity = 10^{20} - 10^{21} Pa s, Lower mantle
734 viscosity = 10^{21} - 10^{23} Pa s), and a melting model (ie., ice history) which, in this case, was the MIN
735 model. The red lines are for Lithospheric thickness $H = 70\text{km}$, upper mantle viscosity = 2×10^{20} Pa

736 s, lower mantle viscosity = 10^{22} Pa s. The blue lines show the case for lithospheric thickness

737 $H=70\text{km}$, upper mantle viscosity = 2×10^{20} Pa s, lower mantle viscosity = 10^{23} Pa s.

738 **Extended Data Figure 8 |**

739 **Comparisons between ANU GMSL and the present new GBR based GMSL.** The blue curves

740 represent the ANU GMSL results⁴ whereas the red bands, covering a range of GBR RSL based

741 GMSL, are from our study. During the transition from LGM-a to LGM-b, around 21 ka, there is

742 enhanced precipitation over the North American Ice Sheet and to a lesser extent over Antarctica,

743 although, for the latter, the ice volume continues to build up, for longer, until the termination of

744 LGM-b at ca.17 ka. The manually adjusted nominal ANU ice model will influence our inferred

745 melting history for each ice sheet. Furthermore, although, the ANU model differs in some

746 respects from other ice sheet reconstructions, eg., (ref. 64) the results from these simulations are

747 not significantly different.

748 **Extended Data Figure 9 |**

749 **GIA model results for HYD and NOG with different viscosity settings.** MAX (a) and MIN (b)

750 represent the maximum and minimum extremes of GBR RSL. Blue and red bands are relative sea

751 level ranges derived from our study for Hydrography's passage (HYD) and Noggin Pass

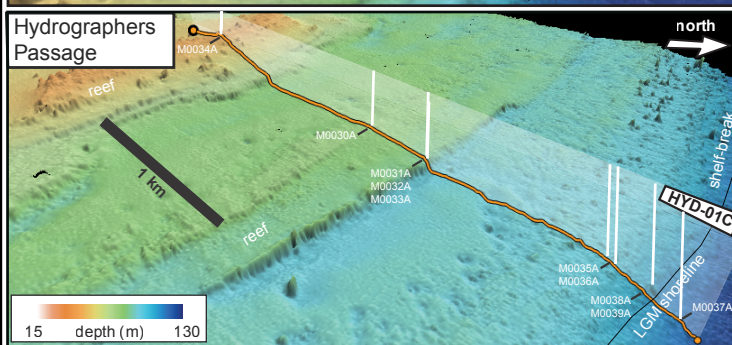
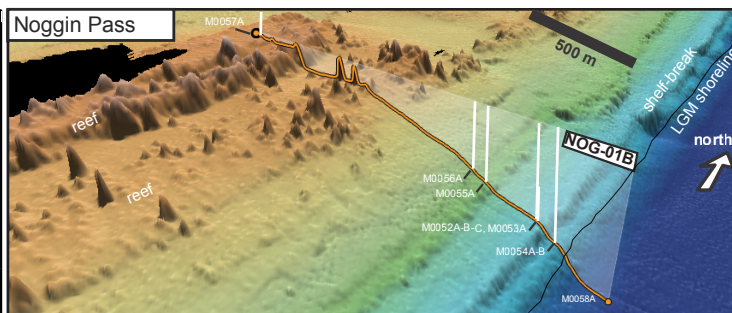
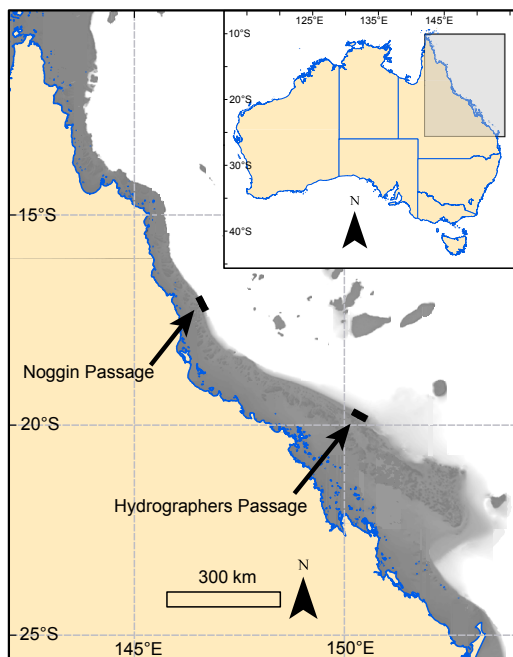
752 (NOG). Gray bands represent the range of predicted sea levels using the new ice
753 model. Lithospheric thickness is fixed at 70 km, whereas mantle viscosities for upper and lower
754 mantle varied between 10^{20} - 10^{21} Pa s and 10^{21} - 10^{23} Pa s. RSL predictions for representative
755 viscosities for HYD-01C and NOG-01B are shown as red and blue solid and dotted lines
756 respectively. V_{up} and V_{low} represent the upper and lower mantle viscosity values (side panel).

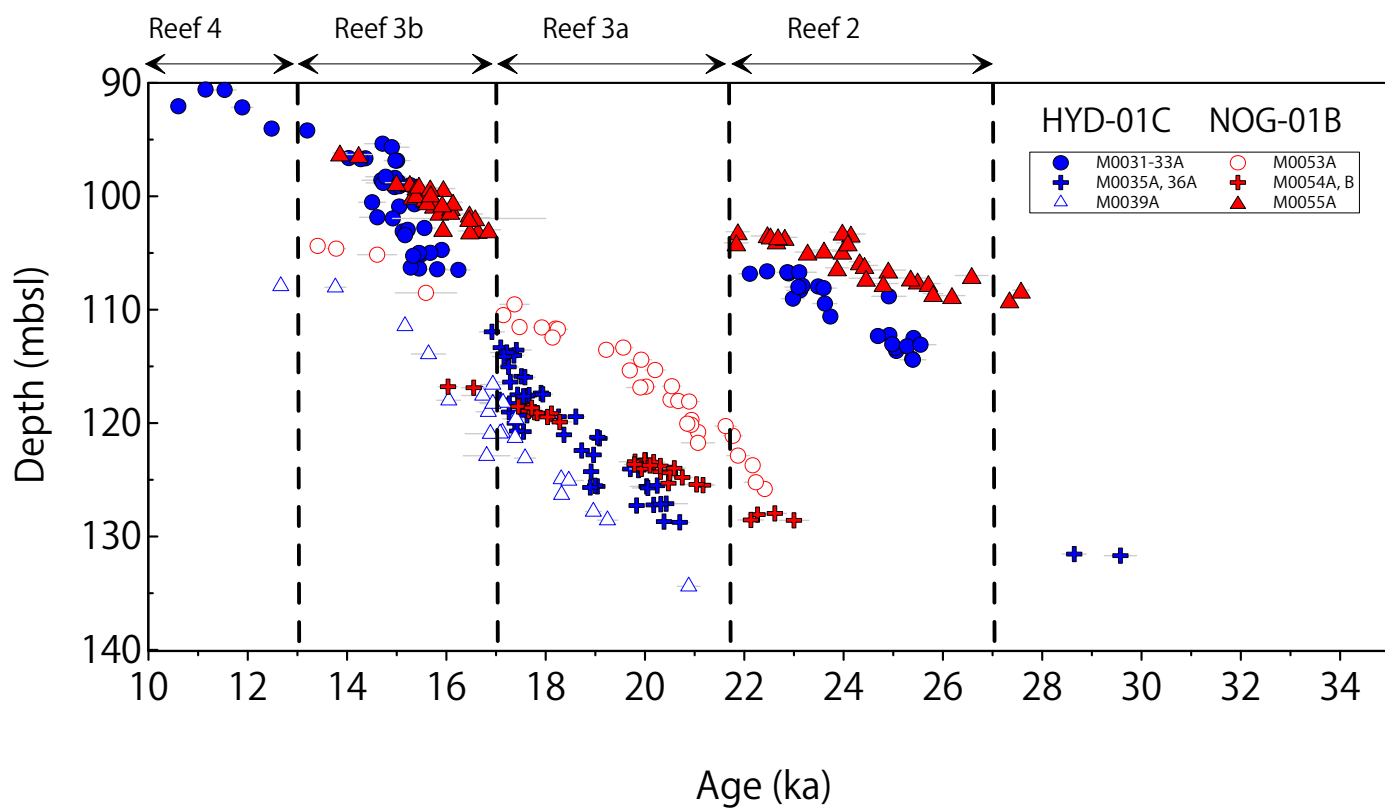
757 **Extended Data Table 1 |**

758 **Simplified coral and coralline algal assemblages and their likely paleoenvironmental**
759 **setting.**

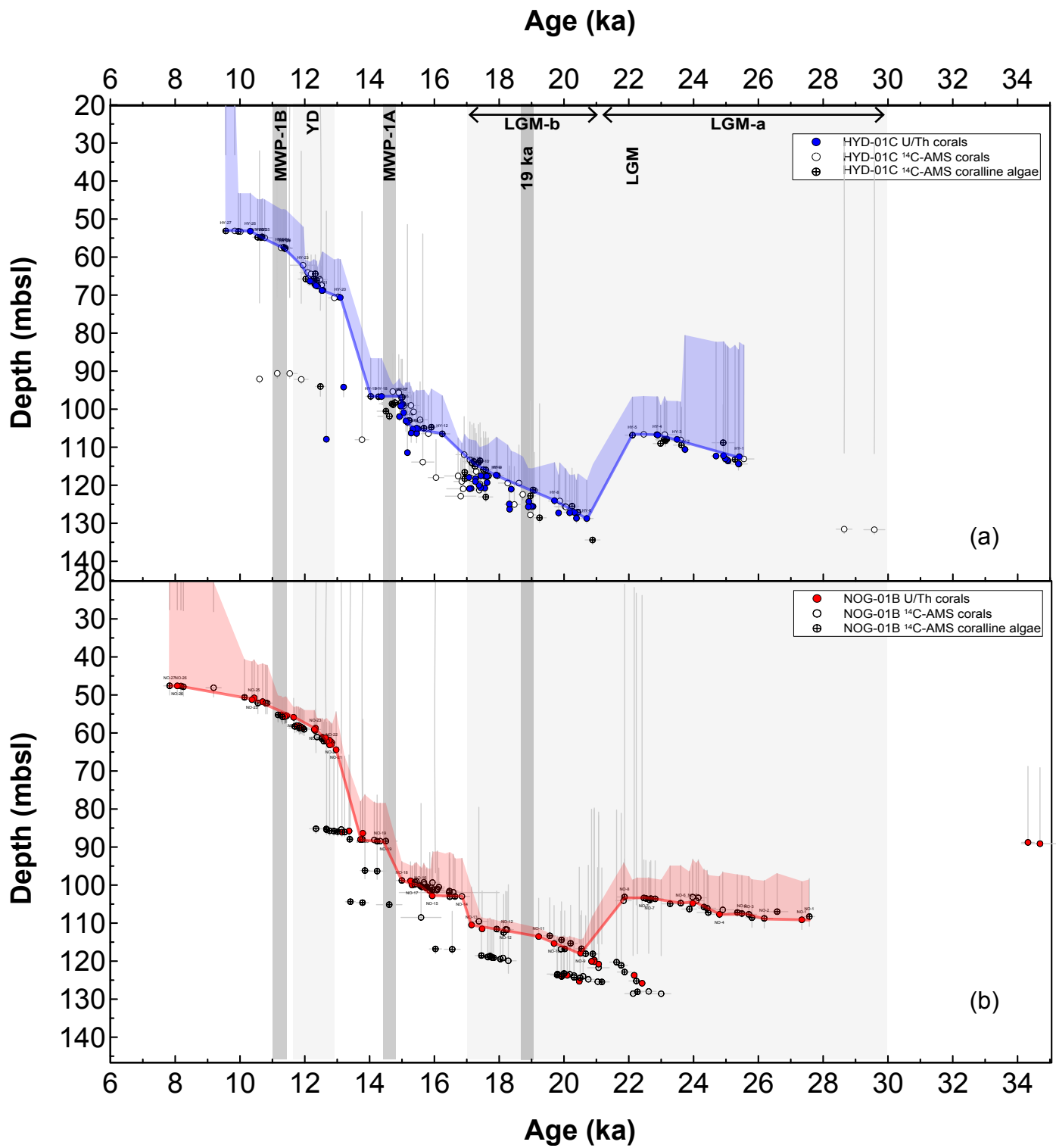
760 *When associated with centimetre-scale thick aA1 CAR crusts and vermetid
761 gastropods. □ **When associated with thin crusts of aA3 and lacking vermetid
762 gastropods. □ ***Paleowater depths were estimated by comparison with their modern Indo
763 Pacific counter parts.

764

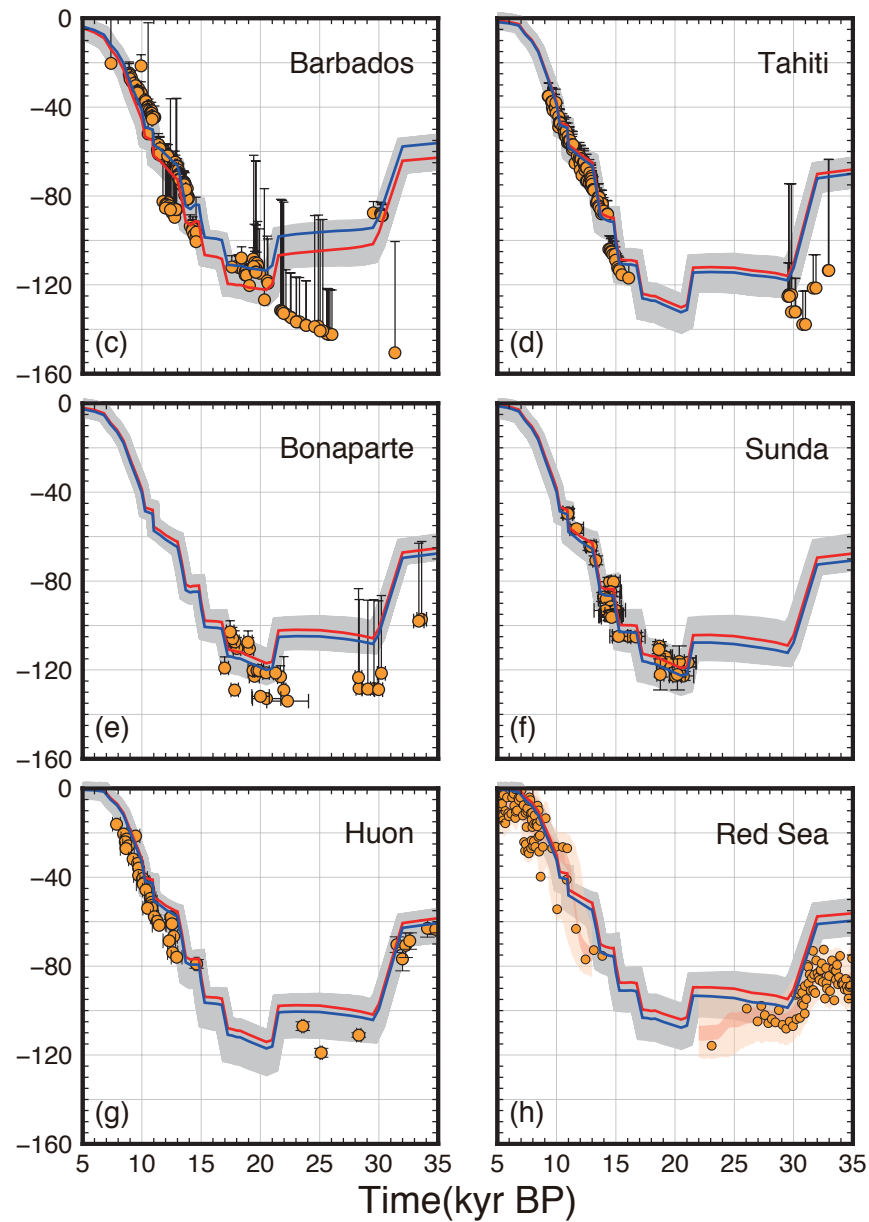
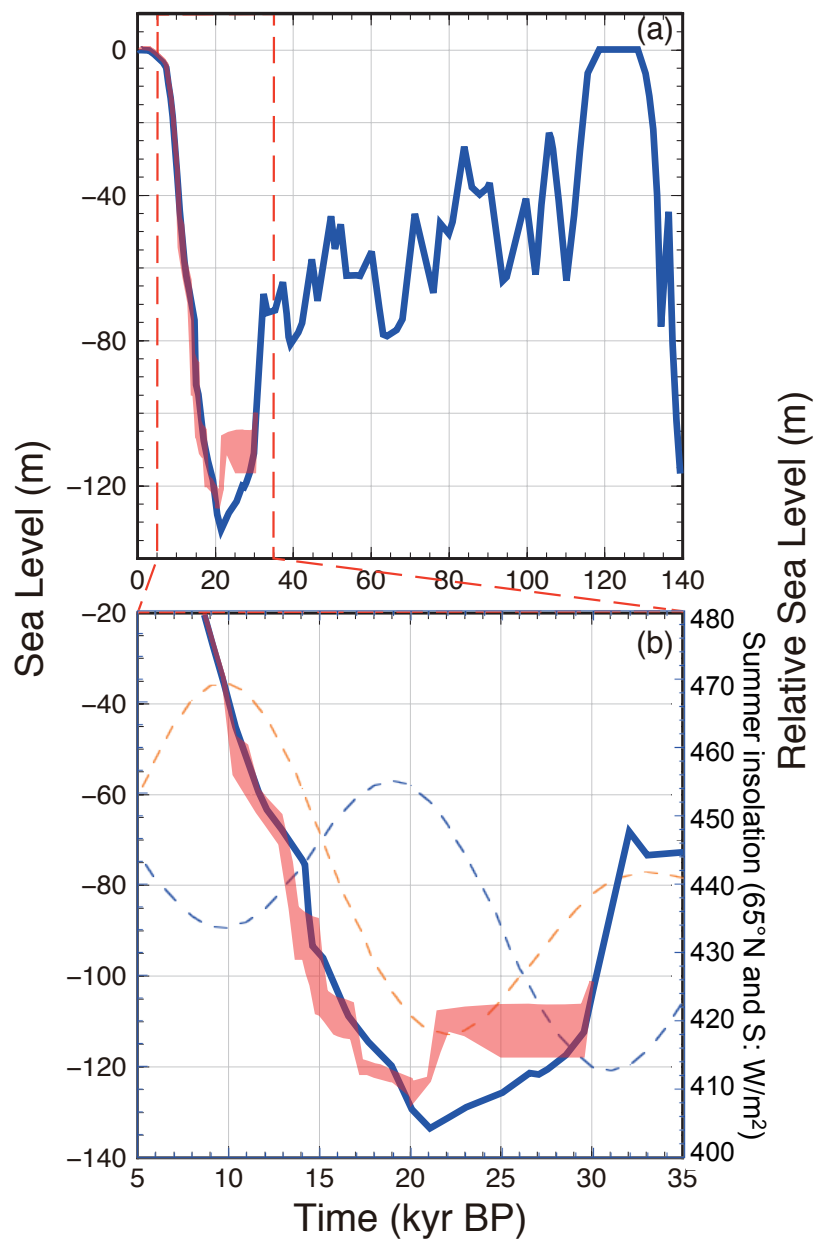




Yokoyama et al. (Fig2)



Yokoyama et al. (Fig3)



Yokoyama et al. (Fig 4)